Does Hypoxic Training Improve Running Economy and Performance of Elite and Competitive Middle- and Long-Distance Runners? A Systematic Review With Meta-Analysis of Randomized Controlled Trials

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[1]MSH Medical School Hamburg, Institute of Interdisciplinary Exercise Science and Sports Medicine, Hamburg, Germany; [2]Department for Exercise Physiology and Sports Therapy, Justus-Liebig-University of Gießen, Gießen, Germany; and [3]Institute of Mountain Emergency Medicine, Eurac Research, Bolzano (South Tyrol), Bolzano, Italy

Abstract

Schwalm, LC, Pilat, C, Nolte, S, Gatterer, H, Krüger, K, and Hollander, K. Does hypoxic training improve running economy and performance of elite and competitive middle- and long-distance runners? A systematic review with meta-analysis of randomized controlled trials. *J Strength Cond Res* XX(X): 000–000, 2026—Altitude training (AT) is used to improve endurance performance in competitive running. The aim of this systematic review was to determine whether hypoxic training interventions affect running economy (RE) and performance of competitive runners compared with training under normoxic conditions. Randomized controlled trials (RCTs) were included if they (a) consisted any exposure to hypoxia over a period of ≥3 weeks while performing an endurance exercise training during the same period, and (b) included RE, time trial (TT), time-to-exhaustion (TTE) tests or $\dot{V}O_2$max under normoxic conditions, and (c) included competitive distance runners. Sixteen RCTs were included in the review and 13 in the meta-analysis. The number of subjects in the included studies were $n = 182$ (11% women) for RE, $n = 95$ (19% women) for $\dot{V}O_2$max, $n = 134$ for TT (14% women), and $n = 81$ (4% women) for TTE. The meta-analysis showed no impact of AT on RE (standardized mean difference (SMD): −0.2; 95% confidence interval (CI): −0.58–0.19; $p = 0.31$; $I^2 = 33\%$). No impact was found for $\dot{V}O_2$max (SMD: 0.33; 95% CI: −0.72 to 1.37; $p = 0.54$; $I^2 = 82\%$) and TT (SMD: −0.34; 95% CI: −0.80 to 0.13; $p = 0.16$; $I^2 = 42\%$). Altitude training showed superiority in improving TTE compared with normoxic training (SMD: 0.89; 95% CI: 0.12–1.66; $p = 0.02$; $I^2 = 56\%$). Available RCTs do not support an improvement in RE, $\dot{V}O_2$max, and TT when AT was compared with normoxic training. Future RCTs should specifically investigate effects of AT on RE in elite athletes.

Key Words: altitude training, hypoxia, endurance, athletics

Introduction

For nearly 60 years, since the 1968 Olympic Games in Mexico, well-trained athletes have included altitude training (AT) in their preparation (26,67,78,81). Since then, a variety of AT approaches have been developed and used by athletes: A first modification of the traditional "live-high-train-high" (LHTH) regimen which typically involves living and training at natural altitude throughout the day for 2–6 weeks, was the "live-high-train-low" (LHTL) approach (41,67). In contrast to LHTH, the training takes place at sea level or low altitudes based on the consideration of maximizing the hypoxic dose without compromising the quality of the workout (9,41,97). Considering the financial, social, and logistical challenges of traveling to natural altitudes, artificial altitudes (e.g., through altitude tents or altitude houses) provide an alternative and individualized access to LHTL training for the athletes (26). In recent years, increasing attention has also been paid to time-efficient intermittent hypoxic exposure (IHE), in which athletes are exposed to a shorter but more intense hypoxic stimulus during rest (21,46,81). Approaches with training under short-term hypoxia are defined as "live-low-train-high" (LLTH) and include various modalities such as intermittent hypoxic training (IHT) or repeated sprint training in hypoxia. The more recent combination, where athletes live at altitude and train both in normoxic and hypoxic conditions, is called "LHTH and low" (HHL) (21,46).

Although AT has been used extensively in endurance sports to improve performance, its effectiveness has remained controversial in research (44,71) due to studies indicating no improvements (72) and reports showing even potential negative effects of chronic hypoxia (i.e., sleep disturbance, immune suppression) that may outweigh the positive effects (21,81). Existing reviews and meta-analyses have focused on investigating the effectiveness of different approaches of AT (e.g., LHTL, LLTH) and the hypoxic dose on exercise performance or maximal oxygen uptake ($\dot{V}O_2$max) as the main outcome (9,21). $\dot{V}O_2$max is a major determinant in middle- and long-distance running performance,

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along with other variables such as the ability to run at a high percentage of $\dot{V}O_2max$ and running economy (RE) (33,37,43). Running economy represents the amount of oxygen or energy required to run at a given steady-state speed and has been shown to have a stronger association with running performance than $\dot{V}O_2max$, although there are some inconsistent results (16,24,47,48). Improved RE indicates a reduced energy cost to run at a certain speed, or to run at faster speeds with the same energy cost (37). It has been demonstrated that improvements in RE that are measured in the laboratory translate into performance improvements during time trial (TT) and time to exhaustion tests (TTE) (32,40,76). For example, the superior performance of East African runners over their European counterparts in recent decades is at least partly due to their better RE (62,80). Despite the typical high altitude at which East African runners train and live, variables such as $\dot{V}O_2max$ do not seem to be superior to those of Europeans, suggesting that altitude may be a factor (62). Interestingly, while effects of AT on performance or $\dot{V}O_2max$ have been the focus of systematic reviews, to the best of our knowledge, there are no systematic reviews that investigated the effects of AT on RE in elite and competitive athletes, although there are indications that AT also affect RE (31,50,54,69). Therefore, this review and meta-analysis aimed to investigate 2 questions: (a) does a hypoxic training intervention (of any type) affect RE and $\dot{V}O_2max$ of elite and competitive runners and hereby alter the endurance performance compared with training under normoxic conditions? and (b) does the effect vary depending on the type of hypoxic training models?

Methods

Experimental Approach to the Problem

We used the guidelines of the Cochrane Handbook for systematic reviews of interventions and followed the checklist (see File 1, Supplemental Digital Content, http://links.lww.com/JSCR/A842) for the Preferred Reporting Items for Systematic reviews and Meta-Analyses 2020 (53). The protocol was prospectively registered on Prospero (Registration Number: CRD42023486341). Registration was completed before searches and screenings were performed.

Eligibility Criteria

The inclusion criteria were as follows: (a) randomized controlled trials (RCTs); (b) studies that included an intervention consisting of any intermittent or continuous exposure to natural or artificial hypoxic conditions, such as LHTL, HHL, LHTH, IHE, LLTH (including varying forms, e.g., IHT) over a period of at least 3 weeks while performing an endurance exercise training program during the same period; (c) studies with outcomes including TT performance in competitions, field tests or laboratory tests, TTE, $\dot{V}O_2max$, or other measures of maximal aerobic capacity or RE under normoxic conditions; (d) studies that included elite and competitive middle and long-distance runners usually engaged in disciplines >800 m. "Elite" and "competitive" was defined as participation on national or international championship level or, if no information was provided, regular competition participation and a $\dot{V}O_2max$ of >55 ml·min^{-1}·kg^{-1}.

The exclusion criteria were: studies not available in English or German; conference abstracts, comments, animal experiments; using additional interventions (e.g., blood flow restriction); estimated (not measured) outcomes; measuring the outcomes under hypoxic conditions; measuring nonrunning outcomes (e.g., economy, $\dot{V}O_2max$, or TT on the bike); assessing acute effects of altitude/hypoxic conditions.

Information Sources and Search Strategy

Four electronic databases (Cochrane Library, Google Scholar, MEDLINE through PubMed, Web of Science) were searched. The searches covered all dates of available literature with the date of the last search being August 26, 2025. No language limits were applied within each database to avoid excluding articles that were not assigned a language. All database-specific search terms were developed by CP and reviewed by SN and LS in advance. The following search term was applied to MEDLINE: ("athletes"[Title/Abstract] OR "endurance athletes"[Title/Abstract] OR "runners"[Title/Abstract] OR "trained runners"[Title/Abstract] OR "elite"[Title/Abstract] OR "elite runners"[Title/Abstract] OR "competitive"[Title/Abstract] OR "competitive runners"[Title/Abstract] OR "athletes"[MeSH Terms] OR "running"[MeSH Terms]) AND ("altitude"[Title/Abstract] OR "altitude training"[Title/Abstract] OR "living high"[Title/Abstract] OR "train high"[Title/Abstract] OR "hypox*"[Title/Abstract] OR ("hypox*"[All Fields] AND "training"[Title/Abstract]) OR ("hypox*"[All Fields] AND "exposure"[Title/Abstract]) OR "intermittent hypox*"[Title/Abstract] OR "interval hypox*"[Title/Abstract] OR "central sensitization"[Title/Abstract] OR "low-oxygen"[Title/Abstract] OR "oxygen deficiency"[Title/Abstract] OR "hypoxia"[MeSH Terms] OR "altitude"[MeSH Terms]). In case of MEDLINE, we additionally applied the Cochrane sensitivity- and precision-maximizing RCT-Filter. In case of Web of Science, the search term was supplemented by the terms "RCT"(TS) OR "randomized"(TS). The Cochrane library was searched without a study design restriction. Google Scholar was searched by applying the term "altitude runners" and considering the first 200 studies by sorting for "best match." In addition, all reference lists were checked for relevant articles at the level of full-text screening. Hand searching of reference lists and forward citation searching of included studies was also used to identify articles. The search string used for all databases but Google Scholar is reported in Supplemental Digital Content, (see File 2, http://links.lww.com/JSCR/A843).

Selection Process

Duplicate references were first removed using the deduplicate function of Endnote 21 (Clarivate Analytics, Philadelphia, PA) and then remaining duplicate references were removed manually (LS, SN). Two authors (LS and SN) independently screened titles and abstracts to determine initial eligibility. Afterward, the authors reviewed the full texts of all articles to determine their eligibility for inclusion based on the eligibility criteria. Disagreements in eligibility decisions were resolved with a third reviewer (KH) when required. We excluded 1 study that did not formally meet the predetermined exclusion criteria but investigated local ischemic preconditioning (73). This case was discussed by KH, KK, SN, LS, and CP, and the decision was made by consensus.

Data Collection Process

Data extraction was completed independently by 2 authors (LS, CP) using a standardized form that was pilot-tested on 2

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randomly selected included studies. The data were then merged by 2 authors (LS, CP) and any discrepancies in the extracted data were resolved through discussion.

Data Items

Extracted data from each full-text article included (a) study information (e.g., corresponding author); (b) study design; (c) sample size; (d) sex; (e) running ability (e.g., participation in national or international championship level); (f) hypoxic regime and duration/hypoxic dose; (g) means and *SD*s of performance measurements, characteristics (e.g., TT distance, TTE speed) and timepoints of measurement; (h) means and *SD*s of $\dot{V}O_2max$ measurements and timepoints of measurements; (i) means and *SD*s of RE measurements and timepoints and characteristics of measurement (e.g., running speeds). If insufficient data were reported, the corresponding authors were contacted by email. When data were not presented in tables or text and when authors did not provide the requested data, these were extracted from figures using WebPlot Digitizer (4).

Risk-of-Bias Assessment

After piloting on 2 randomly selected included studies, all included studies were independently evaluated and rated by 2 reviewers (LS and CP) based on the Cochrane risk-of-bias 2 tool for randomized trials (75). Disagreements in risk-of-bias assessment were resolved by discussion before the scores were merged into a spreadsheet (Cochrane RoB2-templates). The risk of bias was considered in the interpretation of the results by applying the Grading of Recommendations Assessment, Development, and Evaluation (GRADE) system (1). In brief, the overall quality was initially rated as high and downgraded to moderate, low, or very low for each of the following limitations: −1 if ≥ 50% of studies had moderate or high risk of bias, −2 if ≥ 50% had high risk of bias (risk of bias); −1 for serious inconsistency based primarily on visual inspection of forest plots and $I^2 \geq 50\%$, −2 for very serious inconsistency (inconsistency); −1 if ≥ 50% of studies use surrogate marker or did not clearly report data collection methods (indirectness); −1 if confidence intervals (CI) cross 2 thresholds, or if $n < 800$ (imprecision); −1 if suspected, e.g., asymmetric funnel plot (publication bias).

Statistical Analyses

This review conducted meta-analyses through the Review Manager web version (2). A separate Microsoft Excel table served as an additional tool to process numerical data and to decide which studies were eligible for quantitative synthesis. Meta-analyses were performed if at least 2 studies reported relevant data. The changes over time, from pretest (pre) to post-test (post) were considered as effect measures where pre was defined as the latest outcome measurement before the beginning of the intervention and post was defined as the earliest outcome measurement after completion of the intervention. If there were more than 1 intervention group (41,50) or more than 1 intervention period (58), the arithmetic mean out of both intervention groups and the results of the first intervention period were calculated and used for meta-analysis, respectively. Owing to the use of different measurement scales (e.g., absolute vs. relative $\dot{V}O_2max$ values, different running distances and velocities in TT and RE measurements, respectively), we had to deviate from our pre-registered analysis plan to use mean differences. Therefore, all effect measures for continuous data (RE, TT, TTE, $\dot{V}O_2max$) are given as standardized mean difference (SMD) effect sizes and their 95% (CI calculated by Wald-type method). If there were several end points for the same outcome, e.g., present for RE ($\dot{V}O_2$ at different speeds) and TT (different running distances), the arithmetic mean over all end points was calculated for both pre and post and used for meta-analyses. Pooled effect measures were calculated by an inverse variance, random-effect model with a 95% CI. RevManWeb includes the formula for Hedges' (adjusted) g effect size (18). Missing SDs for changes (SD changes) is a common problem in systematic reviews and applies to this review, too. Consequently, we treated this problem as described elsewhere in more detail (83) and proceeded in a stepwise manner. In brief, we first filtered the included publications for additional descriptive data to calculate SDchanges. Second, corresponding authors of the included studies were contacted to request their raw data sets or the *SD* of the changes. Third, the SDchanges were calculated according to the formula:

$$SDchange = \sqrt{SD^2baseline + SD^2final - (2 \times r \times SDbaseline \times SDfinal)}$$

*SD*change means the *SD* of the mean changes from baseline, SDbaseline represents the *SD* of the pretest, SD final corresponds to the *SD* of the post-test, and the r represents the correlation between the baseline and final measurements. As none of the included studies provided enough data to determine a value for *r* according to steps 1 and 2, we assigned a value of 0.7 (10,3) to the formula above to provide a conservative estimate, which is consistent with the approach of Rosenthal et al. (61) and has been widely used previously (7,39,83). In addition, we undertook a sensitivity analysis by imputing an alternative *r* value of 0.5 to test the robustness of the results and did not find any changes of the pooled effect size measures (not shown). A prespecified subgroup-analysis of different hypoxic training regimes vs. normoxic training on short-term changes (from the latest measurement before the intervention and the earliest measurement after the intervention) was performed for RE, TT, TTE, and $\dot{V}O_2max$ according to the pre-registered analysis plan. Effect size interpretation was considered the commonly used interpretation of small (0.2), medium (0.5), or large (0.8). The heterogeneity of a meta-analysis was measured by the chi-squared statistic, and the level of heterogeneity was estimated by the I^2 statistic. I^2 results were interpreted as low (25%), moderate (50%), and high (75%) (30).

Reporting Bias and Certainty Assessment

Reporting bias was assessed as a part of publication bias assessment of the Cochrane risk-of-bias 2 tool for randomized trials.

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Therefore, the assessment of risk of bias due to missing results (arising from reporting biases) will be presented at this place. In addition, funnel plots were created to assess publication bias as a part of GRADE.

Results

Study Selection

The initial literature search yielded 4,825 records through electronic databases (Figure 1). After removing duplicates (n = 582), title and abstract screening resulted in exclusion of 4,199 records. Five records were not retrieved (only abstracts were available in trial registries—searches in the authors' publication lists and attempts to contact them were unsuccessful), resulting in 39 full-texts screened for inclusion/exclusion criteria. Twenty-three records were excluded, resulting in 16 articles from the original search identified as eligible for review. If studies used the same data set, only the first published study was included in the meta-analysis, while the others were only included in the review (Table 2). Thus, 13 studies were included in the meta-analysis.

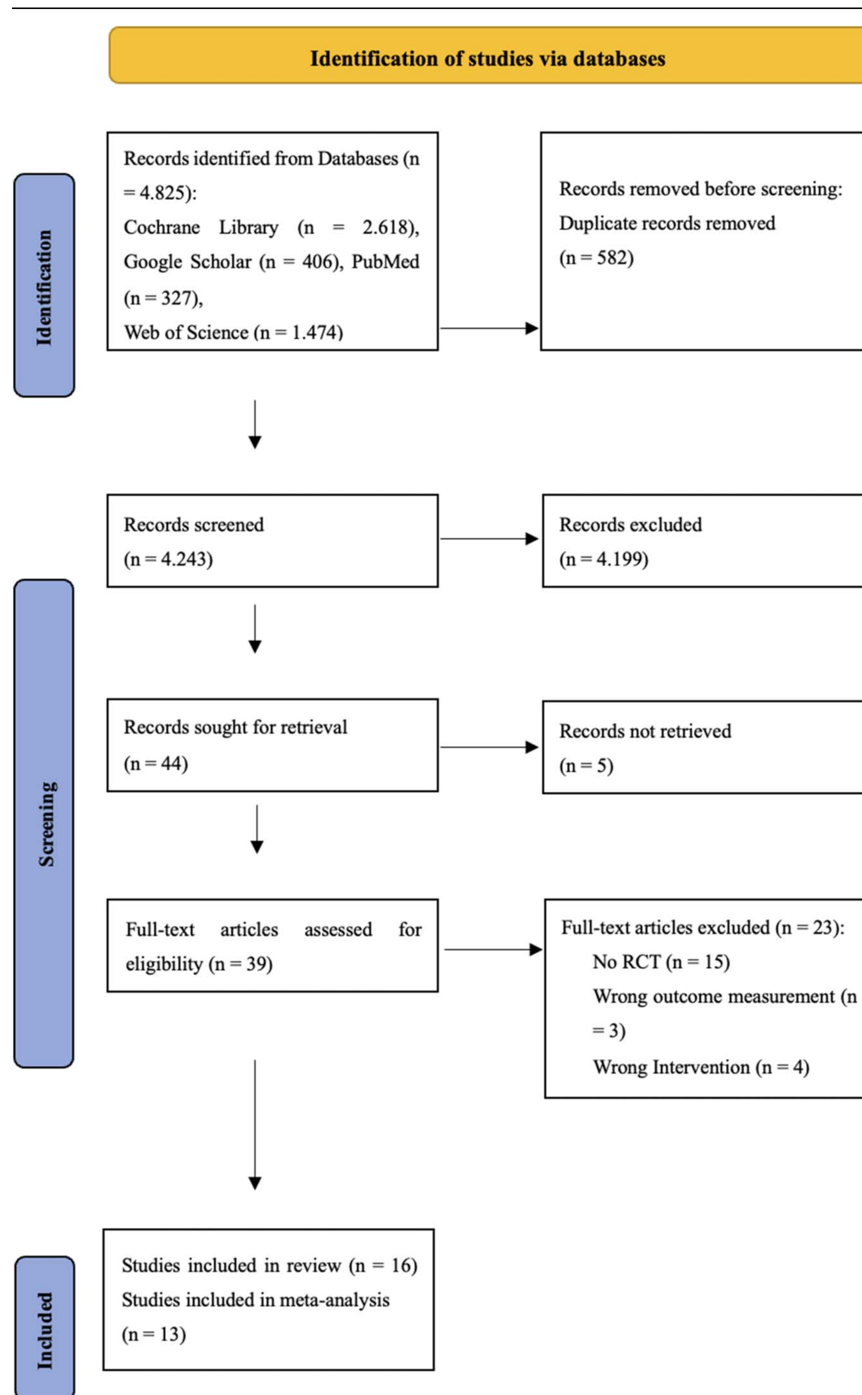

Figure 1. PRISMA flow diagram.

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Study Characteristics

The studies included in the review and subject characteristics, hypoxic regimes, and hypoxic doses are listed in Table 2. Fifteen studies used artificial altitude and only 1 study used natural altitude. Three different hypoxia regimens were investigated in the included studies (IHT (n = 8), LHTL (n = 6), IHE (n = 2)). One study used IHT and LHTL groups (50). All 13 studies included in the meta-analysis provided either TT (22,38,41,54,55,58,60), TTE (13,20,31,50,63), $\dot{V}O_2$max (13,38,41,58,60,69), or RE (13,20,31,38,41,50,54,58,59,69). The total number of subjects in the included studies was n = 182 (11% women) for RE, n = 95 (19% women) for $\dot{V}O_2$max, n = 134 for TT (14% women), and n = 81 (4% women) for TTE. Of the 13 included studies, 10 included only men and 3 included both men and women (overall included women, n = 23). For our main outcome RE, 4 studies assessed RE during 1 speed (31,38,54,60) and 6 studies assessed RE during 2 or more speeds (13,20,41,51,58,69). All studies expressed RE as oxygen uptake per time or distance, in most cases normalized to body weight. The speeds at which RE was measured ranged from 12 km·h^{-1} to just over 19 km·h^{-1} (12 mph). One study used the speed corresponding to the ventilatory threshold (60).

The TT distances ranged from 1000 to 5000 m. One study used 1000 m (22), 3 studies 3000 m (38,55,60), 1 study 4500 m (58), 1 study 5000 m (41), and 1 study combined 3000 and 5000 m TT (54). For TTE, 2 studies used the time during an incremental test (31), 1 study during 95% of the $\dot{V}O_2$max pace (63), 1 study during the pace corresponding to the pretraining $\dot{V}O_2$max (20), and 1 study used the TTE during the $\dot{V}O_2$max stage during an incremental test (50). All $\dot{V}O_2$max measurements were taken during running, only 1 study provided $\dot{V}O_2$max values for a cycling test (55). The latter was not included in the analysis due to a lack of comparability.

Risk of Bias in Studies

The risk of bias scores of the included studies are shown in Figures 2–5. The scores were assessed for each outcome. Most studies were at moderate or high risk of bias for the randomization process and the selection of the reported outcome. Conversely, only a few studies were at high or moderate risk of bias for deviations from the intended interventions, missing outcome data, or outcome measurement. Therefore, the overall risk of bias was moderate for most studies and high for a few.

Results of Individual Studies and Syntheses

Forest plots showing the effects of AT compared with sea-level training for all our outcomes are presented in Figures 2–5. The meta-analysis showed no impact of AT on the main outcome RE (standardized mean difference [SMD]: −0.2; 95% CI: −0.58 to 0.19; p = 0.31; I^2 = 33%). The same was true for $\dot{V}O_2$max (SMD: 0.33; 95% CI: −0.72 to 1.37; p = 0.54; I^2 = 82%) and TT (SMD: −0.34; 95% CI: −0.80 to 0.13; p = 0.16; I^2 = 42%). Altitude training showed superiority in improving TTE compared with sea-level training (SMD: 0.89; 95% CI: 0.12–1.66; p = 0.02; I^2 = 56%). In Figures 2–5, only short-term changes are shown (from the latest measurement before the intervention and the earliest measurement after the intervention). In addition, we performed a medium-term analysis for studies that performed a repeated measurement ≥3 weeks after the intervention. Only 2 studies (n = 24, 0% females) have reported medium-term values for RE, $\dot{V}O_2$max, and TT (Figures 6–8) and found effects on $\dot{V}O_2$max that favored normoxia (SMD: −3.72; 95% CI: −6.91 to −0.58; p = 0.02; I^2 = 0%), but not for RE (SMD: −0,23; 95% CI: −1.05 to 0.58; p = 0.58; I^2 = 0%) or TT (SMD: 0.13; 95% CI: −0.67 to 0.93; p = 0.75; I^2 = 0%). A summary of meta-analysis findings and quality of evidence synthesis is summarized in Table 1 (funnel plots in see File 3, Supplemental Digital Content, http://links.lww.com/JSCR/A844). The quality of the evidence was moderate for RE and TT, and it was very low for $\dot{V}O_2$ max and TTE. The subgroup analysis of different hypoxic training regimes (IHE, IHT, LHTL) did not show preferred regimes for any of the

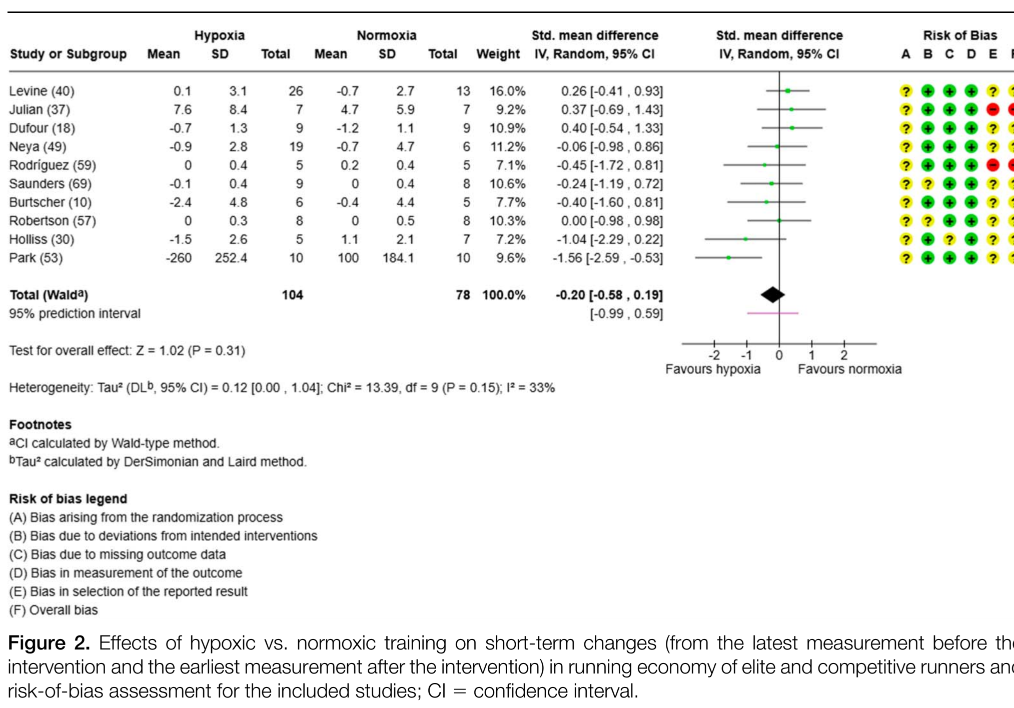

Figure 2. Effects of hypoxic vs. normoxic training on short-term changes (from the latest measurement before the intervention and the earliest measurement after the intervention) in running economy of elite and competitive runners and risk-of-bias assessment for the included studies; CI = confidence interval.

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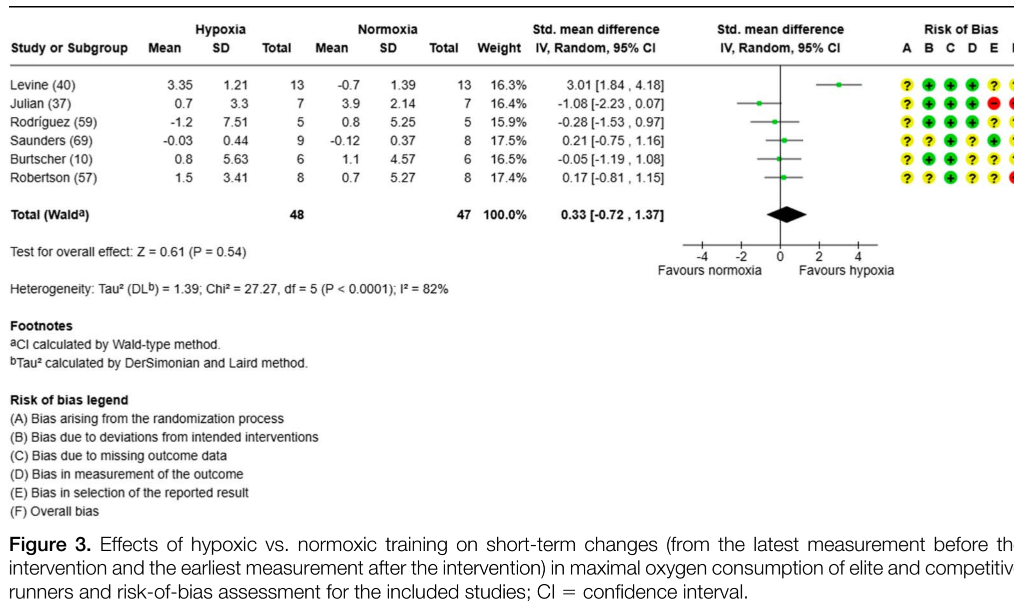

Figure 3. Effects of hypoxic vs. normoxic training on short-term changes (from the latest measurement before the intervention and the earliest measurement after the intervention) in maximal oxygen consumption of elite and competitive runners and risk-of-bias assessment for the included studies; CI = confidence interval.

outcomes (see File 3, Supplemental Digital Content, http://links.lww.com/JSCR/A844).

Discussion

The main findings of our meta-analyses are that the published RCTs do not support an average improvement of AT on RE (moderate GRADE evidence) compared with sea-level training in elite and competitive runners. The same was found for $\dot{V}O_2max$ (very low-GRADE evidence) and TT (moderate-GRADE evidence). Very low-GRADE evidence showed that for TTE AT was superior to the sea-level training. Even if some reviews recommend AT to improve running and exercise economy (global term for economy, not only in running but also in other sports such as cycling or swimming) (5,27), to the best of our knowledge, only 1 other review meta-analyzed exercise economy (not exclusively RE) after AT. In agreement to our findings, Bonetti and Hopkins, who primary focused on performance, did not find changes in exercise economy as a result of AT in a single analysis for different AT regimes (9). They were unable to meta-analyze the effects of exercise economy for different AT regimes due to the small number of studies (9). It must be considered that results from noncontrolled studies, which have been included in their study, can suffer from methodological problems. For example, if AT is also associated with increases in training volume, it is difficult to distinguish whether the changes in RE are due to the change in volume or to AT. The focus of this review on RE in elite and competitive runners, and the inclusion of only RCTs, are both distinctive features of this review.

Despite the overall finding, a number of RCTs in this review showed an improvement in RE (13,31,50,54,69). Consequently, assumptions about the underlying mechanisms have been postulated: As more central adaptations, changes in total hemoglobin mass and concentration after AT are a possible explanation for differences in improvements in RE after AT. Burtscher et al. (13)

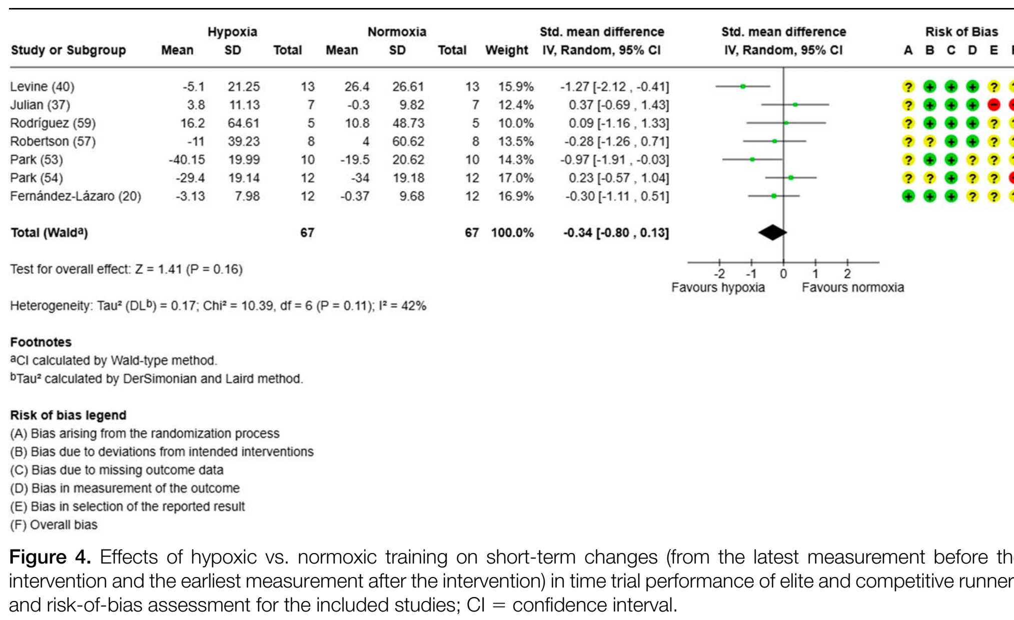

Figure 4. Effects of hypoxic vs. normoxic training on short-term changes (from the latest measurement before the intervention and the earliest measurement after the intervention) in time trial performance of elite and competitive runners and risk-of-bias assessment for the included studies; CI = confidence interval.

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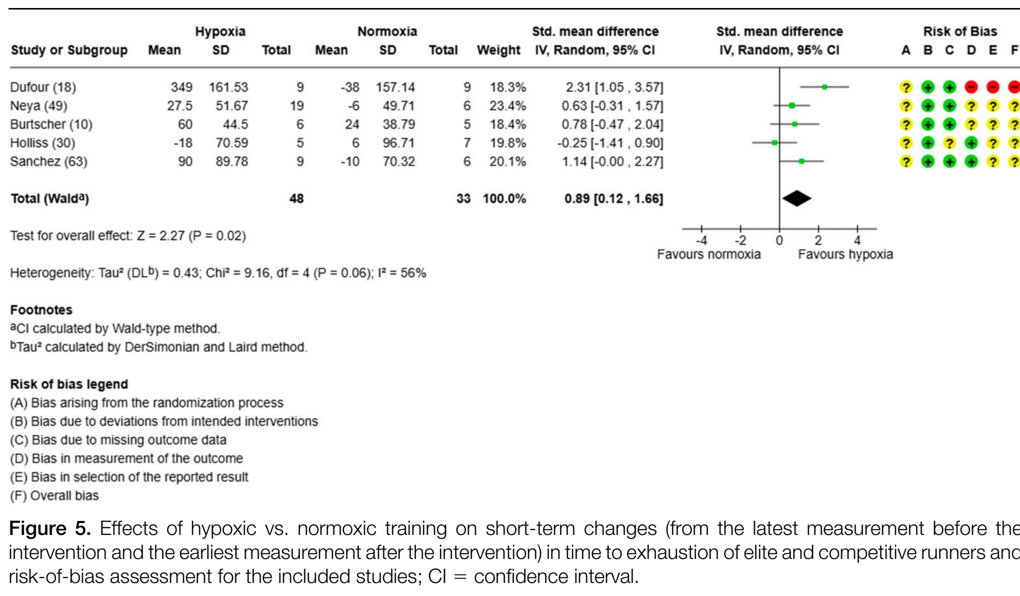

Figure 5. Effects of hypoxic vs. normoxic training on short-term changes (from the latest measurement before the intervention and the earliest measurement after the intervention) in time to exhaustion of elite and competitive runners and risk-of-bias assessment for the included studies; CI = confidence interval.

found that small increases in hemoglobin concentration and hematocrit were closely related to the improvement in RE (mean 2.3%). However, the authors pointed out that the duration of hypoxic exposure was only 30 h during one 5-week period (in this study, two 5-week blocks were investigated, separated by 3 weeks of conventional training) which is unlikely sufficient to increase total hemoglobin mass, but hypoxia may have induced hemoconcentration and optimization of the hematocrit at rest and during exercise (13). Because blood viscosity, as a non-Newtonian fluid, is less dependent on hematocrit at high shear rates (such as during high heart rates), the increased oxygen-carrying capacity may account for the improved RE and performance after intermittent hypoxia at higher cardiac outputs (13). Saunders et al. (69) found that RE improved by 1.0–5.2%, while hemoglobin mass increased by 4.9% (mean), and submaximal HR decreased by 3.1% (mean). The authors suggested a reduction in the cardiorespiratory cost of O_2 transport as a result of the reduction in HR at submaximal running speeds (69). In addition, they postulated that the improved RE after AT could be due to an increase in ATP production per mole of O_2 used or a decrease in the ATP cost of muscle contraction (69). Burtscher et al. (13) suggested that an increased substrate metabolism toward carbohydrate utilization and lower cardiorespiratory costs, such as decreased minute ventilation ($\dot{V}_E$) and HR, contributed to the improved RE after a period of altitude exposure. It is noteworthy that the improvements in RE were greater in the AT group than in the control group only during the first 5 weeks of the 13-week intervention (13). Park et al. also observed parallel reductions in HR and submaximal $\dot{V}O_2$ after 4 weeks of LHTL. Other potential mechanisms for improved exercise economy (not exclusively RE) in the literature are that the physiological mechanisms seem unrelated to reduced ventilation or a substantial shift in substrate use (27). The ability of the excitation and contraction processes to perform work at a lower energy cost and changes in muscle fiber types have been suggested (27,28). Green et al. (28) postulated that a reduced energy requirement of the working muscle may be the result of a reduction in by-product accumulation, such as ADP, inorganic phosphate, and H^+, that occurs after altitude acclimatization. These changes increase the amount of free energy released from ATP hydrolysis and depress the need to maintain hydrolysis rates at preacclimatized levels (28). The assumptions of more peripheral adaptations are compatible with

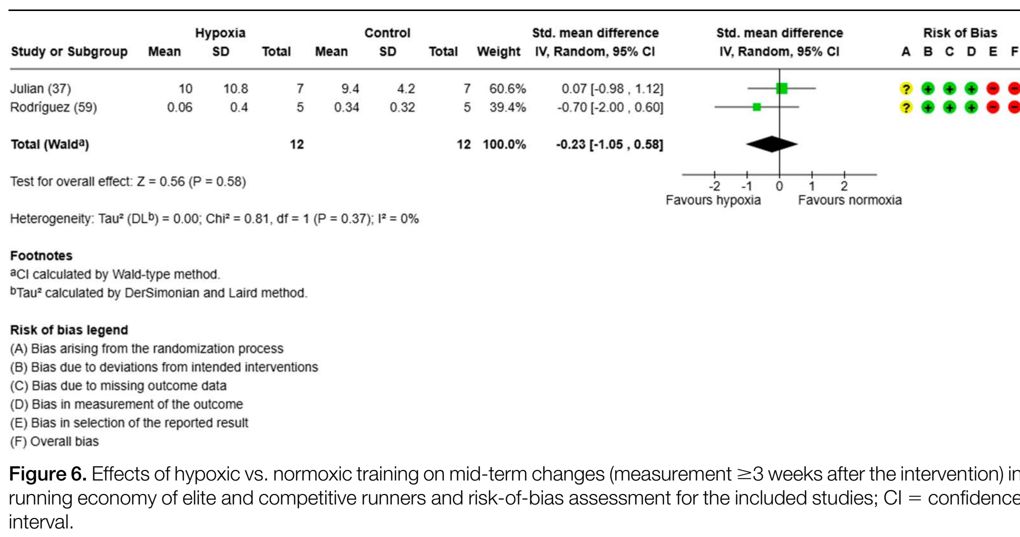

Figure 6. Effects of hypoxic vs. normoxic training on mid-term changes (measurement ≥3 weeks after the intervention) in running economy of elite and competitive runners and risk-of-bias assessment for the included studies; CI = confidence interval.

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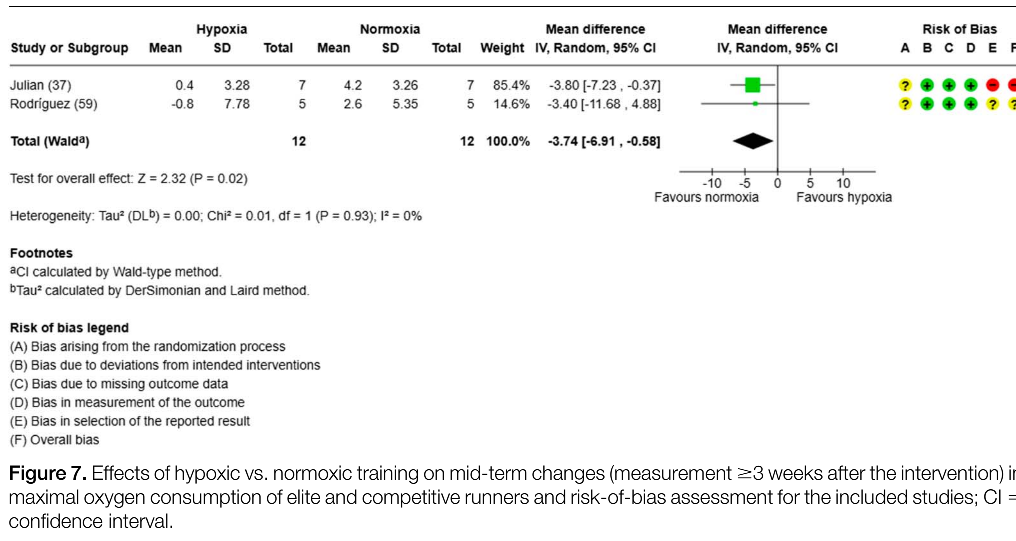

Figure 7. Effects of hypoxic vs. normoxic training on mid-term changes (measurement ≥3 weeks after the intervention) in maximal oxygen consumption of elite and competitive runners and risk-of-bias assessment for the included studies; CI = confidence interval.

the results of Holliss et al. (31) ,which were included in our meta-analysis: the authors suggested that IHT induces adaptations within skeletal muscle that result in a degree of adaptation to hypoxia after they found reduced submaximal $\dot{V}O_2$ after 8 weeks of IHT, while the control group showed increased submaximal $\dot{V}O_2$. They were able to show a reduction in the submaximal HRs, which supports the considerations of reducing RE due to cardiorespiratory adaptations (31). In addition, Neya et al. (50) observed that RE tended to improve after LHTL at lower speeds and was 5% improved at 18 km·h^{-1}, whereas this was not the case for the IHT group and the control group. Because the HR and total hemoglobin mass were unchanged in LHTL, the authors also assumed more peripheral adaptions such as a reduced energy requirement of the working muscle (50).

Given these hypothesized mechanisms and the recommendations of other reviews to implement AT in training to improve RE, the question arises as to why the meta-analysis did not show superior changes in RE after AT compared with sea-level training. Methodologically, it should be noted that the included studies used very different speeds to measure RE and only reported oxygen uptake per distance or time. If the running speeds vary between studies, this will lead to different physiological loads and oxygen consumption values because energy requirements are highly dependent on speed (57). Fletcher et al. (23) found that expressing RE in caloric unit cost may be more sensitive to changes in speed because it accounts for the different ratios of substrates metabolized at different submaximal speeds. It should also be noted that the focus was on elite and competitive athletes. Elite athletes tend to already have much better RE than recreational athletes (6). At the same time, it is suggested that RE improves over several years of training (5). Case study data from world-class runners such as the former marathon world record holder Paula Radcliff support these assumptions (35). The improvements in her performance over the course of her athletic career could be explained mainly by her improved RE, while other parameters, such as $\dot{V}O_2$max, tended to level off (35). Taking this into account, it is possible that the intervention periods in most studies may have been too short, or the effects may have been too small considering the already excellent RE levels observed in highly trained athletes (70). Reference should be made here to the results of Burtscher et al. (13) who were able to observe stronger improvements in RE only during the first 5 weeks of the 13-week intervention phase. The authors explained the differences by the dependence on the training phase since their subjects started after approximately 2 months of recovery after finishing the competition season (13). The considerations regarding the

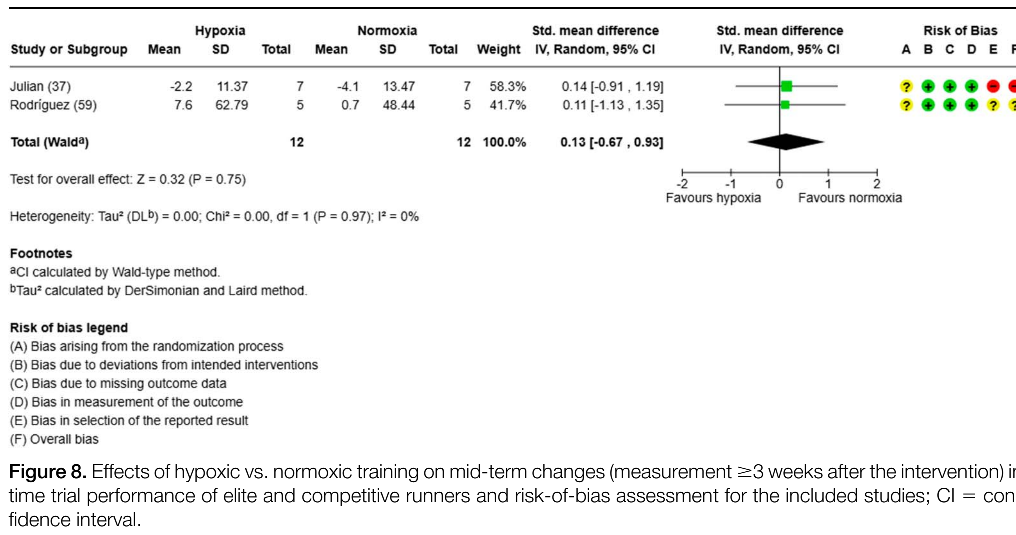

Figure 8. Effects of hypoxic vs. normoxic training on mid-term changes (measurement ≥3 weeks after the intervention) in time trial performance of elite and competitive runners and risk-of-bias assessment for the included studies; CI = confidence interval.

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Table 1

Summary of meta-analysis findings and quality of evidence synthesis.

	Summary of findings				Quality of evidence synthesis (GRADE)					
Outcome	*k*	*n*	Standardized mean difference (95% CI)	I^2 (%)	Risk of bias	Inconsistency	Indirectness	Imprecision	Publication bias	Overall quality
Running economy	10	182	−0.2 [−0.58 to 0.19]	33	−1	None	None	−1	None	Moderate
Maximal oxygen consumption	6	95	0.33 [−0.72 to 1.32]	82	−1	−1	None	−2	None	Very low
Time trial performance	7	134	−0.34 [−0.80 to 0.13]	42	−1	None	None	−1	None	Moderate
Time to exhaustion	5	81	0.89 [0.12 to 1.66]	56	−1	−1	None	−1	None	Very low

possible duration of adaptations and the athlete's level make the results seem to be reasonable, that there was more room for possible improvements at the beginning of the observation (i.e., after the offseason) and that further improvements require more time than was investigated with the study length. Simply extending AT has potential negative effects that may outweigh the adaptations (21,81). Therefore, if the adaptation times for RE are long and the possible positive effects in elite and competitive athletes are small, the approach observed in practice of performing repeated AT with sea-level sojourns in between would also make sense in long-term improvements in RE. However, it must be emphasized that the interaction between training volume and training consistency in improvements in RE over several years of training is currently unclear and more research is necessary (5).

The subgroup analysis of IHE, IHT, and LHTL revealed no favorable AT regimen for any of the outcomes. Although the subgroup analysis were prespecified and restricted to 4 outcomes, it must be remembered that they are inherently observational (3). Therefore, the results of the subgroup analyses should be interpreted cautiously as exploratory rather than definitive, especially

Table 2

Eligible studies with various protocols of natural and artificial altitude.*

References	Subjects	Altitude type	Intervention	Control
Burtscher et al. (13)	11 male/female runners Tier 3	Artificial altitude (normobaric hypoxia), IHE	3 d·wk^{-1} for 2 × 5 weeks at 3200–5500 m, 2 h·d^{-1}	LLTL
Dufour et al. (20)	18 male runners Tier 3	Artificial altitude (normobaric hypoxia), IHT	2 sessions/week for 6 wk at 3000 m, 24–40 min/session	LLTL
Fernández-Lázaro et al. (22)	24 male runners Tier 3	Artificial altitude (normobaric hypoxia), IHT	7 sessions/week for 8 wk at 4000–5500 m, 90 min/session (5 min under hypoxic conditions, followed by 5 min of normoxic conditions)	LLTL
Holliss et al. (31)	12 male runners Tier 3–4	Artificial altitude (normobaric hypoxia), IHT	2 sessions/week for 8 wk at 2150 m, 40 min/session	LLTL
Kim and Park et al. (55)	24 male runners Tier 2	Artificial altitude (normobaric hypoxia), LHTL	>12 h per day for 21 d at 3000 m	LLTL
Julian et al. (38)	14 male runners Tier 3	Artificial altitude (normobaric hypoxia), IHT	5 sessions/week for 4 wk at 4500–5500 m, 70 min/session (5 min under hypoxic conditions followed by 5 min of normoxic conditions)	LLTL
Levine and Stray-Gundersen (41)	26 male/female runners Tier 2–3	Natural altitude, LHTL	4 wk at 2,500 m, 16–20 h·d^{-1}	LLTL
Neya et al. (50)	25 male runners Tier 2–3	Artificial altitude (normobaric hypoxia), LHTL Artificial altitude (normobaric hypoxia), IHT	10–12 h·d^{-1} for 29 d at 3000 m 12 sessions in 31 d at 3000 m, 30 min/session	LLTL
Park et al. (54)	20 male runners Tier 2	Artificial altitude (normobaric hypoxia), LHTL	>16 h·d^{-1} for 4 wk at 3,000 m	LLTL
Ponsot et al. (56) †	15 male runners Tier 3	Artificial altitude (normobaric hypoxia), IHT	2 sessions/week for 6 wk at 3000 m, 24–40 min/session	LLTL
Robertson et al. (58) ‡	16 male/female runners Tier 3	Artificial altitude (normobaric hypoxia), LHTL	14 h per day for 2 × 3 weeks at 3000 m separated by a 5-wk washout period between	LLTL
Rodríguez et al. (60)	10 male/female runners Tier 2	Artificial altitude (hypobaric hypoxia), IHE	3 d·wk^{-1} for 5 wk at 4000–5500 m, 3 h·d^{-1}	LLTL
Sanchez et al. (63)	15 male runners Tier 2–3	Artificial altitude (normobaric hypoxia), IHT	3 sessions/week for 6 wk at 5000–5500 m, 60 min/session (5 min under hypoxic conditions followed by 5 min of normoxic conditions)	LLTL
Saunders et al. (69)	18 male runners Tier 4	Artificial altitude (normobaric hypoxia), LHTL	46 d at 2,860 m, 9 h·d^{-1}	LLTL
Trujens et al. (77) §	10 male/female runners Tier 2	Artificial altitude (hypobaric hypoxia), IHE	3 d·wk^{-1} for 5 wk at 4000–5500 m, 3 h·d^{-1}	LLTL
Zoll et al. (84) †	15 male runners Tier 3	Artificial altitude (normobaric hypoxia), IHT	2 sessions/week for 6 wk at 3000 m, 24–40 min/session	LLTL

*Tiers corresponding to McKay et al. (42), LHTL = live high train low; LLTL = live low train low; IHE = intermittent hypoxic exposure; IHT = intermittent hypoxic training $\dot{V}O_2$max: maximal oxygen consumption.
†Same data set as Dufour et al. Therefore, only Dufour et al. included in meta-analysis.
‡Only first altitude block included in meta-analysis.
§Same data set as Rodríguez et al. Therefore, only Rodríguez et al. included in meta-analysis.

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when few studies contributed to the subgroups. To the best of our knowledge, it is unknown to what extent the possible adaptation mechanisms (e.g., central or peripheral) contribute to improvements in RE. There are indications that the hypoxic exposure of IHT is inadequate to substantially alter hematological parameters and potential mechanisms are specific molecular adaptations in peripheral tissues (21). Considering this, its noteworthy that Neya et al. (50) were able to demonstrate changes in RE in LHTL but not in IHT. At the same time, responses to different modalities of hypoxia have been discussed controversially, especially in the area of artificial hypoxia: acute adaptive responses such as ventilation or fluid balance between hypobaric and normobaric hypoxia (45,79) seems to be different, but not in chronic adaptations such as hemoglobin mass increases, plasma erythropoietin or performance after AT (29,65,66). In addition, the different training intensities, training characteristics, and running speeds used in the interventions should be considered (Table 2 summarizes an overview over the interventions). It is suggested that the speed that is habitually run is the most economical (36). Regarding interval training, it is suggested that very high-intensity running is not effective in improving RE, possibly because of a loss of running technique at very high running speeds or an inability to complete sufficient training volume to produce a training effect on biomechanical variables (5). If the running speed of the training is altered due to AT (e.g., with LHTH or IHT) to maintain the same physiological intensity (i.e., lower running speed at altitude), speed-dependent biomechanics (12) (e.g., contact time and flight time) are altered. Because RE is usually measured at submaximal pace, it could be that by maintaining physiological intensity, the time spent at submaximal intensity has altered from the biomechanical perspective, which may influence the changes (82). In this regard, it is noteworthy, that a nonrandomized study from Saunders et al. (68) showed a 3.3% improved RE across 3 submaximal running speeds after 20 days of simulated LHTL in elite runners. However, this study was not included in the analysis due to the duration and study design. These multiple factors show how difficult it is to make statements about the influence of AT on RE and must be seen as a starting point for more research in this area.

The results regarding $\dot{V}O_2max$ (low GRADE evidence) are in contrast with reviews that focused on maximal aerobic capacity. Feng et al. (21) showed in a Bayesian model-based network meta-analysis that LHTL, LHTH, and IHT outperformed normoxic training in improving $\dot{V}O_2max$. It seemed that the LHTL approach might be particularly effective which is in line with other recent meta-analysis (15,21). As they also investigated the optimal hypoxic dosage using the "kilometer hour" model (kmh = (m/1,000)× h, where "m" represents the altitude of the exposure environment and "h" represents the total exposure duration) (25), they found that a reasonable range for LHTH was 470–1,130 kmh and LHTL 500–1,415 kmh with an inverted U-shaped curve relationship (21). However, it should be noted that there is no common and well-accepted metric to define hypoxic dose, and that such models as "kilometer hour" may be affected by the miscalculation involving low altitudes, which are below the threshold for physiological adaptation for very long periods of time (26). In contrast to our review, Feng et al. only used "athletes" as inclusion criterion, while this meta-analysis exclusively focused on elite and competitive runners. There are indications that athletes may show a levelling off in $\dot{V}O_2max$ development after some endurance training years (34,64,74). Therefore, potential effects in this studied cohort might be smaller. This is in line with the meta-analysis of Bonetti and Hopkins, who found very likely enhancements with LHTH in subelite athletes but not in elite athletes (9).

The meta-analysis showed superior improvements in TTE (very low-GRADE evidence) but not in TT (moderate-GRADE evidence) after AT compared with sea-level training. It has to be considered that previous research has shown that maximal sustainable duration at exercise thresholds, i.e., TTE, exhibits a high coefficient of variation and varies substantially on an interindividual level (19). Moreover, TTE at fixed intensity is not considered an accurate measure of endurance performance, but rather a measure of endurance capacity (17). Measuring the best achievable performance over a predefined time, i.e., a TT, is more suitable and more closely reflects endurance performance (11). It should also be noted that the study of Dufour et al. (20), which we rated as having a high RoB, had a major impact on the overall effect regarding TTE. However, we have decided to include TT and TTE in the analysis due to the presumed small number of studies. In a narrative review, Bonato et al. (8) found significant performance benefits in running-based TT performance in 4 studies using a hypoxic dose of 1,620–1,680 kmh, while 2 studies using 42.3 and 330 kmh showed no improvements. Bonetti pooled data of runners, cyclists, and swimmers, and TT and TTE tests and found that substantial enhancements in subelite athletes were very likely with artificial brief intermittent LHTL, likely with natural LHTL, possible with artificial long continuous LHTL, but unclear for LHTH, artificial brief continuous LHTL, and LLTH while enhancements in elite athletes were likely with LHTL but unclear for all other protocols (9). Rodríguez and Àvila concluded in their systematic review that the evidence supports the concept that LHTL and HHL offer the best potential for performance benefits in collegiate/club runners and elite swimmers, but highlighted the difficulty of comparing existing studies and the small number of controlled trials (59). Our results are in line with this. The small number of RCTs and the different test formats (such as TTE or TTs) make it difficult to detect effects in a meta-analysis, even if the results of studies of lower quality (without a control group) point in this direction. It should also be emphasized that the TT distances of the included RCTs seem short. Of course, 3000–5000 m events are primarily determined by aerobic capacity, but the effects may be stronger over longer distances. This should be taken into account, given that some forms of AT may also influence training intensity, as previously mentioned.

One major limitation is that fewer than 20% of the included subjects were female, making it difficult to draw conclusions about both sexes. Our analysis also did not include studies with individuals who were less fit, but who may show larger effects. In addition, variable interindividual responses should be considered. Levine et al. demonstrated the broad range of individual responses to AT for both performance and $\dot{V}O_2max$ (14). They suggested that the number of nonresponders to AT may be minimized by individualizing living and training altitudes (e.g., based on the erythropoietic response to acute altitude) (14). Interindividual responses may also be related to iron stores and the immune system (49,52). More high-quality RCTs especially in female athletes are needed here, specifically investigating the effects of AT on RE in elite athletes.

There are limitations with combining results for RE across studies given the variation in protocols, gas-analysis equipment, data averaging techniques, and differences in maximal aerobic capacity. In addition, our search criteria resulted in mainly artificial altitude study designs (only 1 natural altitude study) and almost exclusively IHT, IHE, and LHTL studies remaining for analysis. This limited methodology should be taken into account.

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Regardless of the outcome, no single study had an overall RoB2 rating higher than "some concerns." The body of evidence is limited because only RE and TT showed a moderate, whereas $\dot{V}O_2max$ and TTE showed a very low quality of evidence.

Although single studies have found improvements in RE, the overall results of RCTs do not support improvements in RE, $\dot{V}O_2max$, and TT due to AT compared with sea-level training in elite and competitive runners. There is very low evidence for improving TTE by AT. As the present body of evidence suffered from some degree of bias throughout the included studies, we recommend that future RCTs should be more accurate in both adopting of and reporting on randomization procedures, publishing prespecified study protocols, and more specifically investigating the effects of AT on RE in elite and female athletes.

Practical Applications

The use of AT by coaches and athletes does not seem to be suitable for improving RE. There is low evidence for the benefits of AT on capacity tests such as the TTE. Although it is widely used in competitive sports, the importance of AT may be overestimated.

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